SUMMARY OF RESEARCH REPORT

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Shock Wave Dynamics in Weakly Ionized Gases

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I. Overview

We have begun a comprehensive series of analyses and experiments to study the basic problem of shock wave dynamics in ionized media. Our objective is to isolate the mechanisms that are responsible for the decrease in the shock amplitude and also to determine the relevant plasma parameters that will be required for a drag reduction scheme in an actual high altitude hypersonic flight. Specifically, we have initiated a program of analyses and measurements with the objective of (i) fully characterizing the propagation dynamics in plasmas formed in gases of aerodynamic interest, (ii) isolating the mechanisms responsible for the decreased shock strength and increased shock velocity, (iii) extrapolating the laboratory observations to the technology of supersonic flight.

II. A Determination of Drag Reduction Modalities

Plasma related drag reduction schemes may be broadly divided into two main approaches:
(i) The reduction of aerodynamic drag and related boundary layer control issues using a uniform glow discharge atmospheric plasma in contact with the surface of the aircraft. This approach seeks to reduce the level of boundary layer turbulence and/or suppress the formation of turbulent vortices thus reducing the drag coefficient of the aircraft in the atmosphere.
(ii) Drag reduction especially relevant to hypersonic flight at high altitude which is based on the dynamic characteristics of acoustic perturbations in a weakly ionized plasma.

The latter approach appears to be the line pursued by the Russians in a series of experiments performed in the 1980's.[1,2,3] In these experiments a shock wave generated in a neutral gas was admitted into a glow discharge plasma. The main results can be summarized as follows:
(a). When a shock wave enters a plasma its propagation velocity significantly increases beyond the maximum thermal velocity of the shock front in an unionized gas at a comparable temperature.
(b). The strength of the shock (measured directly with pressure transducers and also inferred from density ratios) is weaker in the plasma than in a neutral gas.
(c). The width of the layer of shocked gas behind the front is broader than the shock layer in a neutral gas.

(d).A transverse magnetic field of appropriate value causes a disappearance of the above mentioned acceleration effect and restores the strength of the shock wave.

These observations can be considered to be consistent with the observation of a two-fold decrease of the drag on a sphere moving in a plasma. It was clear to the Russians that the plasma temperature was inadequate in explaining the anomalous dynamics of shock waves in weakly ionized plasmas. The following possible explanations were therefore considered.

1. In experiments conducted in air, nitrogen and other molecular gases, it was proposed that inelastic collisions between plasma electrons and molecules could result in a significant non-equilibrium "trapping" of vibrational energy. [1,4,5] This stored energy, when released behind the shock, could result in the observed abnormal shock dynamics. Two main problems with this model had to do with the observation of anomalous shock dynamics in plasmas formed from monatomic gases as well such as argon and xenon, and also a failure to account for the observed influence of a transverse magnetic field.

2. A second mechanism attributed the formation of an electrical double layer which was observed in certain experiments to electron density gradients in the shock wave and a high electron mobility. This resulted in electron diffusion relative to ions, leading to an electric potential jump on the shock wave front. The large electron velocity was supposed to result in an increase in the electron density ahead of the shock and to account for the formation of a thermal precursor. The increased shock velocity and reduction in amplitude were attributed to the gas heating due to this precursor.

3. A third model assumed that a mechanism operated to convert some of the energy in an incident shock wave into kinetic energy of the neutral particles ahead of the shock front. This energy transfer was thought to be implemented by ion acoustic waves excited by the shock front. The appearance and rapid damping of these ion waves would give rise to a thermal precursor ahead of the shock front with the result that the neutral particles gain kinetic energy and the velocity of the shock wave in the plasma increases.

The possibility of exploiting the properties of weakly ionized plasmas for aviation applications requires that a complete and coherent explanation that is consistent with all the observations be found. The speculated role of ion acoustic needs to be investigated experimentally.

A weakly ionized plasma is a medium composed of neutral particles, positively charged ions and free electrons. It is expected that when a density perturbation is applied to such a medium a variety of wave phenomena will result. In particular, the normal sound wave which is carried by the neutrals with a propagation velocity of $c_s = \sqrt{\frac{\gamma kT}{M}}$ will likely be accompanied by waves carried by the ions which do not require collisions to propagate. These so called ion acoustic waves are established by coulomb interactions between the ions and propagate at a higher velocity $v_s = \sqrt{\frac{kT_e + \gamma kT_i}{M_i}}$. Ion acoustic waves can propagate even when the ions are cold, i.e. $T_i \rightarrow 0$. In this case $v_s = \sqrt{\frac{kT_e}{M_i}}$. Indeed in most cases, ion acoustic waves are observed to propagate only when $T_e \gg T_i$. These waves are damped either through ion collisions with the neutrals or through collisionless Landau damping which occurs when the wave phase velocity $v_s \approx v_{th}$, where $v_{th} = \sqrt{\frac{kT_i}{M_i}}$ is the ion thermal velocity.

When a stronger density perturbation is applied (say by an aircraft traveling at supersonic speed) and an acoustic shock is created carried by the neutrals, it is possible to have ion acoustic waves generated at the shock front which propagate ahead of the shock into the upstream gas where they may be damped. This precursor effect can result in an increase in the velocity of the neutral particles with the result that the shock wave velocity in the plasma increases and also the energy in the shock is not localized as in a neutral gas, resulting in a weaker shock strength. The broadening of the shock layer and weakening of the shock strength observed by the Russians may be indicative of the initial shock energy transferred to ion acoustic waves.

The response of a column of plasma to an acoustic wave pulse has been studied by a number of authors. Ingard and Shulz for example,[6] consider the response of a plasma to a weak shock by looking at the perturbations in ion density and electric field associated with a weak shock introduced in the neutral gas component. They show that although the density perturbation in the neutral gas remains a step function (i.e. the form assumed for the acoustic pulse), the resulting ion density profile is not step-like but decreases exponentially from a peak value to zero in front of the shock. That is, an ion wave with a non-zero width runs ahead of the neutral shock front.

A large amplitude ion wave may lead to the formation of an ion acoustic shock wave in the plasma medium. The physics of the propagation of such a shock is essentially equivalent to a sheath moving through a plasma. It is perhaps in this regard that the Bohm Sheath Criterion (mentioned by the review author) is relevant. In this case the shock speed u, must satisfy the inequality $v_s<u<1.6v_s$ where $v_s = \sqrt{\frac{kT_e}{M_i}}$, the ion acoustic speed.

The ion acoustic speed has no explicit dependence on density. However, the temperature and the degree of ionization of a plasma depend on the plasma density in a form given by the Saha equation $\frac{n_i}{n_o} \approx 2.4\times10^{24} \frac{T^{3/2}}{n_i} \exp(-E_i/kT)$, where E_i is the mean ionization potential of the constituent atoms. Given a fixed supply of power, the maximum electron and ion temperatures attainable and hence the ion acoustic speed are directly dependent on the volume and density of gas particles to be ionized.

In hypersonic flight at high altitude, typical pressures lie in the torr - mtorr range, i.e. $n_o \sim 10^{16}$ - $10^{13} cm^{-3}$. For a few percent ionization, the required electron temperature is of the order ~0.6 eV or higher. The corresponding ion temperature may be much lower and the ion acoustic speed will typically be ~2 km/s. A laboratory experiment set up to investigate the role of ion acoustic waves in the anomalous dynamics of shock waves in plasmas must cover a parameter range as follows: $n_o \sim 1$ mtorr - 1 torr, $T_e \sim 0.1$ eV to a few eV, in gases such as nitrogen and air of aerodynamic interest.

III. Experimental Results

Drag reduction on hypersonic flight through a decrease in the strength of the bow shock is of significant importance to aviation technology. Our plasma-based drag reduction scheme seeks to exploit the anomalous dynamics of shock waves in weakly ionized gases as suggested by previous investigators. These investigations reveal similar features in non-equilibrium molecular gases (e.g. air, nitrogen) as well as monatomic gases (argon, xenon, etc). At the present time, however, there is no coherent model to explain all the observations. Therefore, using argon and air plasmas with electron density of the order of 10^{12-13} cm^{-3}, neutral density ~10^{16-17} cm^{-3}, and electron temperature 1-3 eV, we are performing a series of experiments with the objective stated above.

The experimental apparatus is shown schematically in Fig. 1. A shock wave (typically Mach 2) is initiated by rupturing the diaphragm separating the high and low-pressure sections. The shock front propagates first in the neutral gas section and is then admitted into a glow discharge plasma formed in argon or air at a few Torr. The discharge is maintained by a D.C. high voltage, constant current supply (≤100 mA, 2 kV). Varying the mean discharge current density controls the plasma degree of ionization. The plasma gas temperature is monitored with a *chromega/alomega (Omega)* thermocouple and the optical spectral radiation with two spectrometer and photomultiplier stations. The dynamic characteristics of the shock wave such as its velocity and strength are monitored using *Kistler* 606A pressure transducers from initiation in the neutral gas, through the glow discharge plasma and beyond until it is reflected off the end-wall. In this way, the effect of the plasma on the shock wave can be fully characterized.

In Fig. 2, some preliminary results are presented for shock waves in argon. The percent change in shock wave velocity when the shock enters the glow discharge tube is shown with and without plasma in the tube. These results show that for pre-plasma shock speeds of 750m/s to 870 m/s there is an average increase of about 5 to 15% in shock speed when the shock wave enters the plasma section. This increase in shock speed does not appear to increase significantly with the temperature mesured with the thermocouple. There appears therefore to be a real plasma effect on the dynamics of the shock.

IV. Plans

Currently, this investigation is being extended over a wider range of shock and plasma parameters in order to identify regimes of shock velocity enhancement and strength reduction. An analysis of the effect of the gas temperature is also being carried out, including a comparison of the thermocouple results with the width (FWHM) of a number of neutral and singly ionized argon spectral lines. These observations will be characterized as a function of the following parameters: (i) neutral particle density, n_o, (ii) plasma electron density, n_e and temperature, T_e, (iii) plasma degree of ionization n_i/n_o and (iv) shock wave Mach number. The plasma parameters are determined with three electric probes biased at an appropriate voltage with respect to the plasma. These measurements will be confirmed by a further study of the spectral radiative emission using a 0.275-m, high-resolution diffraction grating monochromator.

We will study the analytic problem of the electron density profiles in the vicinity of the shock propagating in the plasma. Electron density gradients and consequent diffusion across the shock front will be calculated using the usual one-dimensional equations of continuity and momentum for the charge species. Electron energy transfer occurring through collisions with the upstream plasma particles and the resultant heating of the neutral gas will then be calculated. This gas heating mechanism will be compared to a mechanism that involves the plasma ions through ion-acoustic waves. Assuming an acoustic pulse in the plasma generates ion waves, which propagate ahead of the shock front, wave damping through either ion-neutral collisions or collisionless Landau damping will be calculated to estimate the degree of gas heating. Using the new higher gas temperature, predictions will be made on the dispersion and acceleration of the shock front in the weakly ionized plasma.

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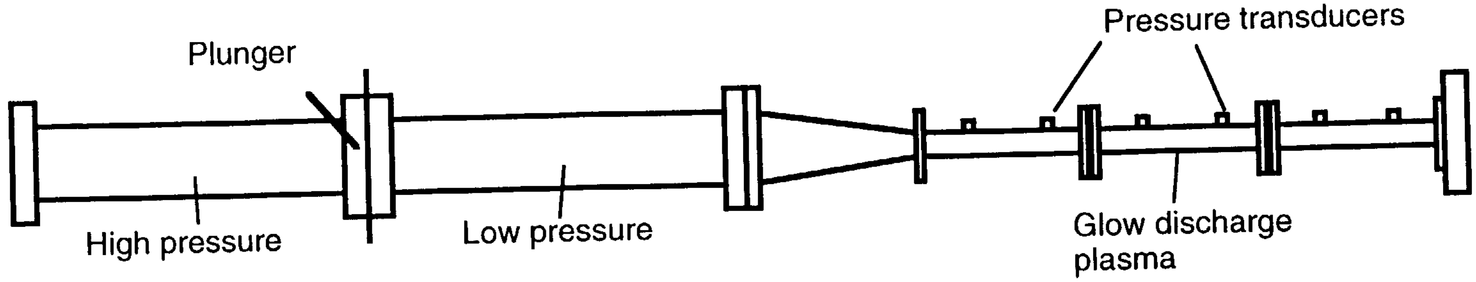

Fig. 1 Schematic of experiment

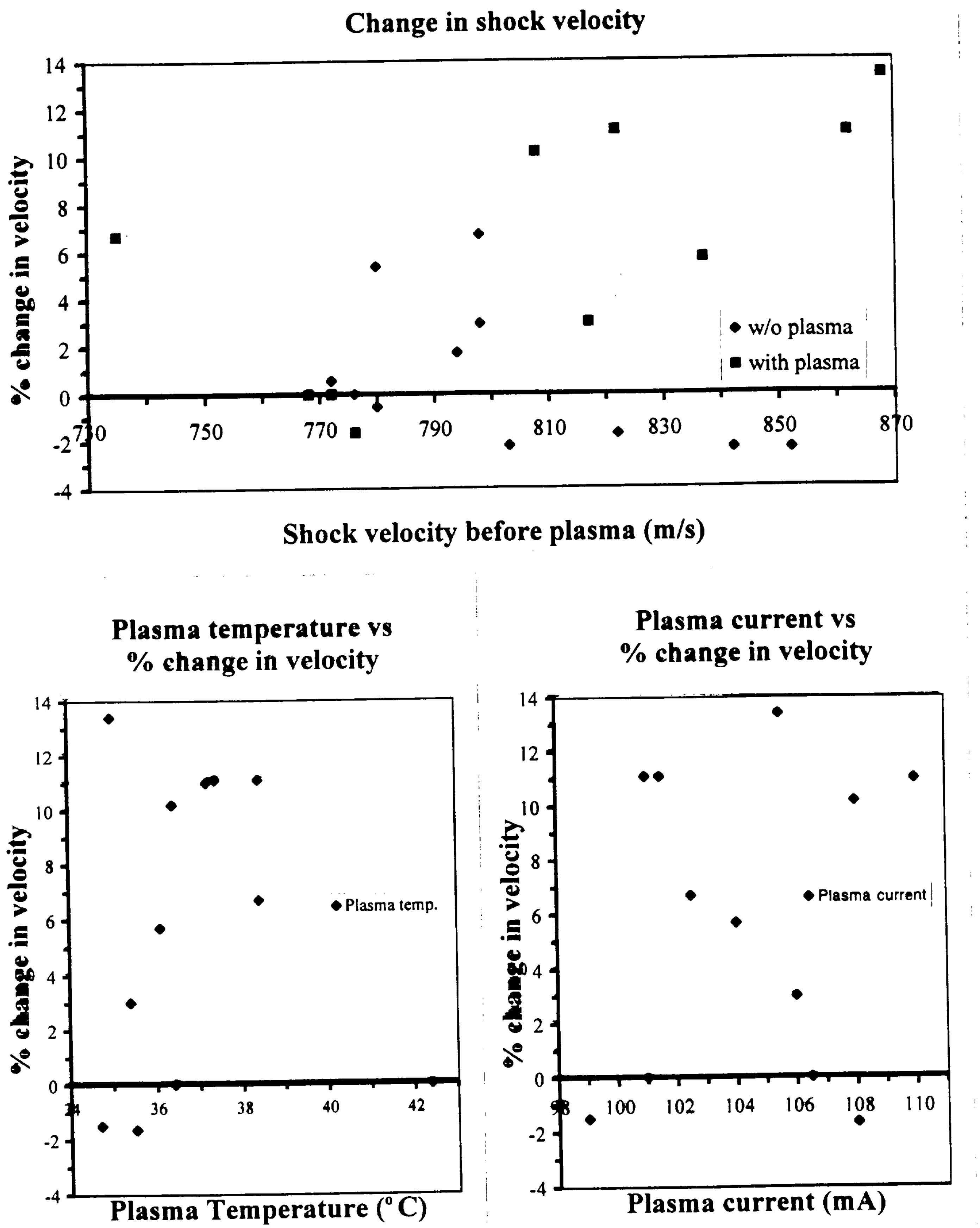

Fig. 2. Overview of Measurement Results